SHAKING TABLE TESTS ON REINFORCED EMBANKMENT MODELS

ESSAIS DE "SHAKING TABLE" SUR DES MODELES REDUITS DES REMBLAIS RENFORCES

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SYNOPSIS: On a 3.0x3.0 m shaking table model embankments reinforced with non-woven materials were shaken in seven cases. In all cases the direction of the vibration was horizontal, parallel with the cross-section. Six cases were examined in two steps to determine the vibration characteristics and the failure behaviour of the models. In one case the model was shaken by simulating the pattern of the Niigata Earthquake in 1964. This paper summarizes the results of these studies. The study emphasize the role of scale factor, slope angle, reinforcement and virtual cohesion in model tests and helps it to design more economical structures which better answer the purpose by investigation the model of the prototype.

INTRODUCTION

To obtain strong earth construction was always a goal from the ancient time. Steel wires began to be used from the last century. The modern method of earth reinforcement is dated back from the invention of Henry Vidal of France. The development of the petrolchemical industry further influenced these methods making new reinforcing materials. The researchers started to examen the possibilities of using reinforced earth to get better earthquake resistance in 1986. Later Koga at al. (1988), Watanabe at al. (1988), Telekes at al. (1991) and Telekes (1992) published their paper about their shaking table tests on reinforced embankment models.

THE DESIGN OF THE TESTS

During the design of the model tests the law of similarity was developed to "Tensar" type reinforced embankments. For "Tensar" type reinforced structure in most cases the law of similarity can be defined as:

$$\tau_y=\tau_2 \qquad (1)$$

where: τ_y = yield shear stress
τ_2 = friction resistance of the soil

Based on the law of similarity developed to "Tensar" type reinforced soil for these experiments, if λ scale were taken into account it can be presumed that the real structure will behave similarly as the model does. Therefore the external safety will be automatically satisfied by using the law of similarity.

TESTS PROCEDURE

On a 3.0•3.0 m shaking table seven model embankments were shaken. The models scale were determined to keep the rule of similarity.
The model scales used in these experiments are 1/6 and 1/9. The excitation of six models were conducted under sinusoid wave loading and one model was shaken according to the Niigata Earthquake seismogram. During the shaking tests the vibration parameters were measured in 24 points of the embankment bodies. The earth pressure was measured at three points in the models body and the strain of the reinforcing materials were also registered at ten points. The measured data went through a calibration equipment and were recorded by PCM Data Recorder. The width of the models were two metres. The direction of the vibration was horizontal, parallel with the cross-section in each case. The movement of the models were recorded by two video cameras, one was above the models in vertical direction and the other was placed in perpendicular direction to the slope surface of the models. From the cameras the data went to a video track. Both the PCM data recorder and the video track were connected to a personal computer. In all cases surface load (burden load) were applied. The set up of the experiments are shown in Fig. 1.
To the shaking table experiments Niigata sand were used. The index properties of Niigata sand determined by Tokida at al. (1987) are as follows:
G_s=2.68; e_{max}=1.00; e_{min}=0.61; D_{60}=0.35mm; D_{10}=0.17mm
The grain size distribution curve of Niigata sand sample is shown in Fig. 2.
At the shaking tests the water content of the Niigata sand was 3% to omit the virtual cohesion as much as possible.
To follow the similarity rule "Tensar" type Geogrid SS-1 was used to the experiments.
The excitation of the models which were shaken with sinusoid wave were carried out in two steps.
1.a. To determine the vibration characteristics of the models a constant 50 gal acceleration was used with variable frequencies from 5 Hz to 50 Hz in 5 Hz steps.
1.b. To determine the eigenfrequency a constant 50 gal acceleration was used with variable

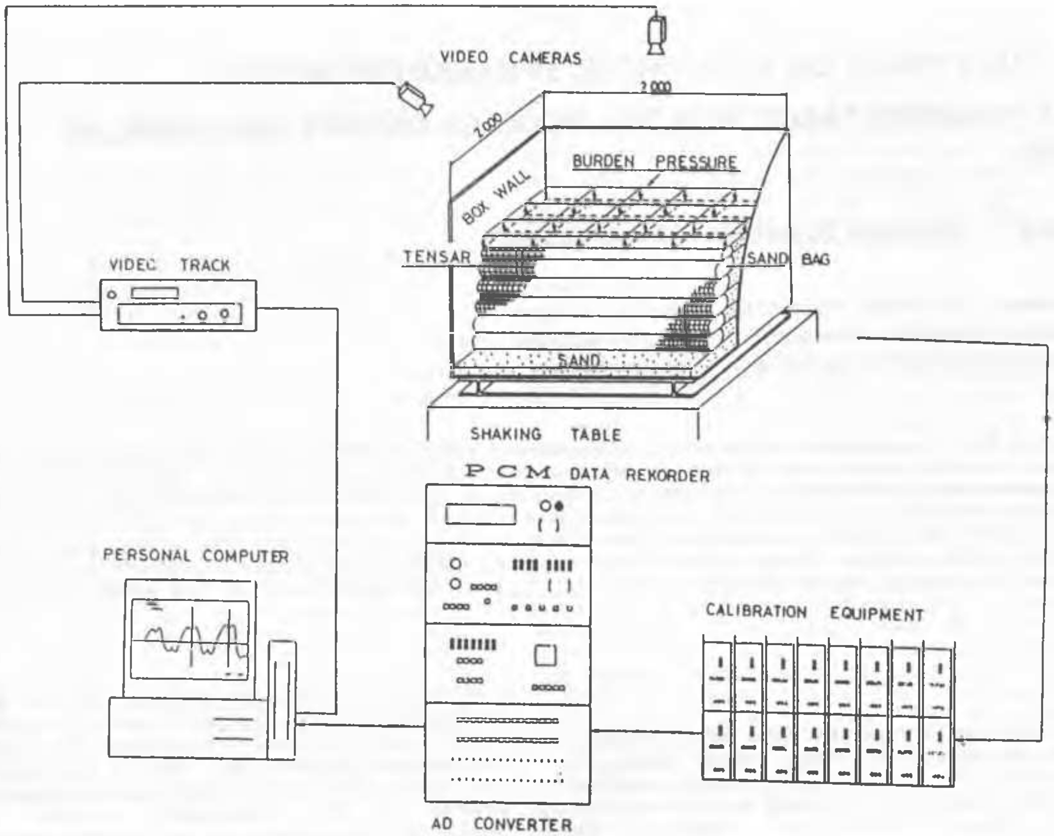

Fig. 1. The set up of the experiment

TABLE 1 The excitation parameters of the models using sinusoid wave

Step	Excitation parameters	
	acceleration	frequency
1.a	50 gal constant	5-40 Hz in 5 Hz steps
1.b	50 gal constant	in the surrondings of the peak values in 1 Hz steps
2.	50-200 gal in 50 gal steps 200-500 gal in 100 gal steps	7.2 Hz constant at scale 1/6 models 10.8 Hz constant at scale 1/9 models

frequencies in 1 Hz steps in the surroundings of the peak value gained from step 1.a.
2. To study the failure behaviour of the models variable accelerations were used from 50 gal until 500 gal in 50 gal steps from 50 gal to 200 gal and in 100 gal steps from 200 gal to 500 gal.

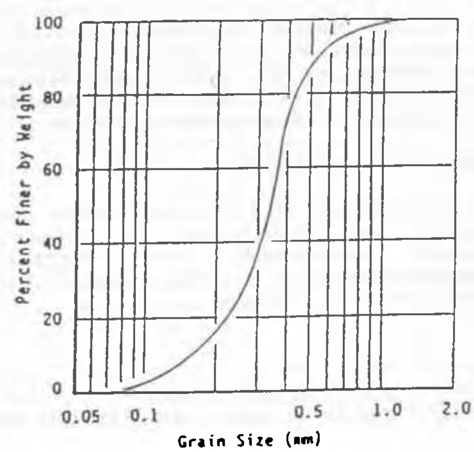

Fig. 2. Grain size distribution curve of Niigata sand sample

The frequency was constant 7.2 Hz. to the scale 1/6 models and 10.8 Hz to the scale 1/9 models. These frequency values were determined from the scale factor between the prototype and the model and the frequency of the Niigata Earthquake to follow the rule of similarity.
The excitation parameters of the models using sinusoid wave are shown in Table 1.
In Case 7 the excitation was carried out according to the simulation of the Niigata Earthquake in 1964. The "design" earthquake was

calculated from the original earthquake spectrum by a computer program named 'SHAKE'. To follow the similarity rule 'Tensar' type Geogrid SS-1 was used to the experiments.

The parameters of the models were as follows:

Case 1. A scale of one ninth model with the slope angle of 1:0.2; having a surface load of 428 kg/m^2; with reinforcement; were shaken by sinusoid vibration. The failure mode was assumed to occur by reinforcement rupture.
Case 2. A scale of one sixth model with the slope angle of 1:0.2; having a surface load of 642 kg/m^2; with reinforcement; were shaken by sinusoid vibration. The failure mode was assumed to occur by reinforcement rupture.
Case 3. The same type of model than in Case 2 were shaken. The failure mode was assumed to occur by pulling out the reinforcement.
Case 4. The same type model than in Case 1 were shaken. The failure mode was assumed to occur by pulling out the reinforcement.
Case 5. A scale of one ninth model with the slope angle of 1:1.5; having a surface load of 428 kg/m^2; without reinforcement; were shaken by sinusoid vibration.
Case 6. The same type of model than in Case 5 with reinforcement were shaken. The failure mode was assumed to occur by pulling out the reinforcement.
Case 7. The same type of model than in Case 3 were shaken by a simulation seismogram of the Niigata earthquake in 1964.
The parameters of the models are shown in Table 2.
The location of the accelerometers and earth pressure meters in a model are shown in Fig. 3.

THE TEST RESULTS

The vibration characteristics of the models

The acceleration response ratios (the value of the acceleration measured in the body of the embankment at the location of the different channels and divided by the acceleration of the shaking table) were determined for all cases. One of the results is shown in Fig.4.
The comparison of the peak acceleration response ratios and eigenfrequencies of the models are shown in Fig. 5.
From the experiment Step 2 the original shape and the shape after failure are shown in Fig. 6-9.
Case 1 and Case 4 are not failed till 500 gal.
The eigenfrequency of the prototype was calculated and found to be 4 Hz. The eigenfrequency of the prototype was backcalculated from the models eigenfrequencies take into account the scale ratio of $\lambda^{-3/4}$ from the law of similarity give the results as follows:

From the one sixth model, in Case 3: eigenfrequency= 4.4 Hz,
From the one ninth model in Case 4: eigenfrequency= 3.8 Hz.
The results from the models well matched to the eigenfrequency of the prototype.
The shape of the acceleration response ratio of the prototype can also be predicted well from the model.
The failure characteristics of the models does not fit well with the theory.

TABLE 2 The parameters of the models

Case	Slope angle	Model scale	Reinforcement	Failure mode	Excitation wave
1.	1:0.2	1/9	Y	rupture	sinusoid
2.	1:0.2	1/6	Y	rupture	sinusoid
3.	1:0.2	1/6	Y	pull out	sinusoid
4.	1:0.2	1/9	Y	pull out	sinusoid
5.	1:1.5	1/9	N	-	sinusoid
6.	1:1.5	1/9	Y	pull out	sinusoid
7.	1:0.2	1/6	Y	pull out	earthquake simulation

scale: mm
length: 2000 mm
burden pressure: 428 kg/m^2
▼ measurement of acceleration in vertical direction
●○ measurement of acceleration in horizontal direction
Ch1-Ch18 accelerometers in the embankment body
Ch19 accelerometer on the bottom of the sand box
Ch20-Ch22 registration of displacement from acceleration by double integration
Ch23 registration of voltage from the controller to the shaking table
Ch24 accelerometer on the shaking table
Ch25-Ch27 horizontal earth pressure meters

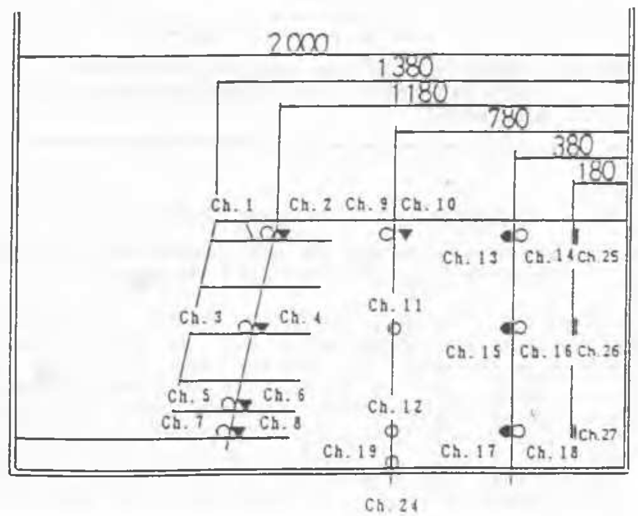

Fig. 3. The location of accelerometers and earth pressure meters in Case 1 and Case 4

The reason of this is explained below:
- To evaluate the result of failure test it is necessary to take into account the cohesion of the soil. In the calculation the cohesion of the Nigata sand was neglected and was calculated as zero. However it is in the safety side of a statical stability analysis, but in reality the fine sand always has some cohesion. The small cohesion in the model backcalculated to the prototype is not a negligible value. In our case the Niigata sand which was used for the models at the water content of 3 % has a small 0.755 kPa cohesion. This value is backcalculated to the prototype from the one sixth model resulted 4.53 kPa cohesion and backcalculated from the one ninth model resulted 6.79 kPa, we belive these

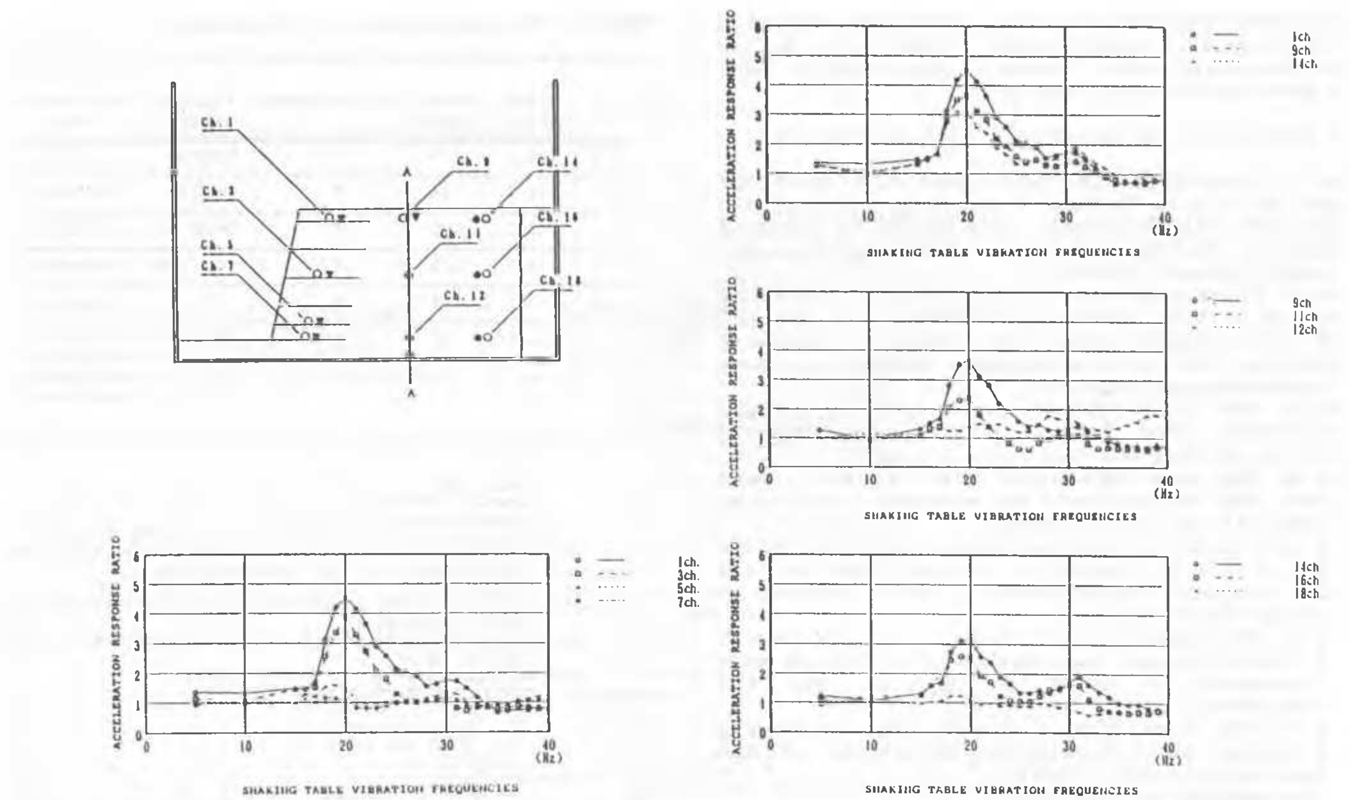

Fig. 4. Comparison of the peak acceleration response ratios and eigenfrequencies of the models

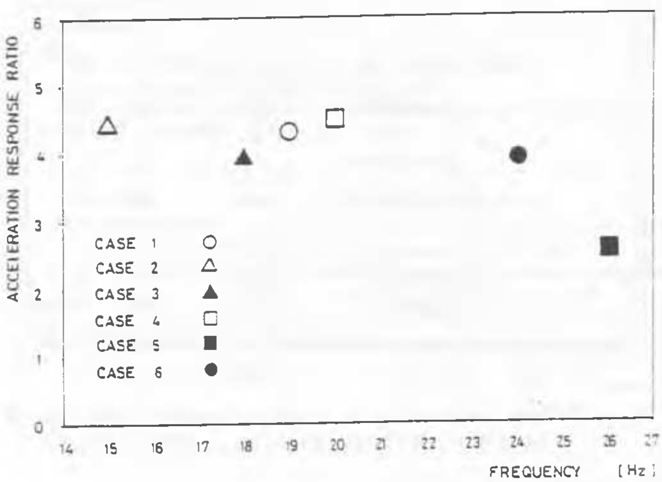

Fig. 5. Comparison of the peak acceleration response ratios and eigenfrequencies of the models

are not negligible values during a failure analysis, even though in the design manual of 'Tensar' the cohesion is neglected.

The effect of the scale of the models

The effect of the scale of the models can be analyzed from the results of Case 1, Case 2, Case 3 and Case 4. Case 1 and Case 2 were the same following the law of similarity in any means except the scale as Case 3 and Case 4 were also the same.The comparison of the acceleration response ratios are made from the measured data in step 1 of Channel 1 in each cases, because the top of the slope is the most critical point in dynamic analysis. The comparison is shown in Fig. 10-11.

The eigenfrequencies of the models in Case 1 and Case 2 are a little smaller than, that of Case 4 and Case 3, respectively. The observed differences are due to the discrepancy of stiffness of the models which was designed to be smaller if the failure occures by reinforcing material rupture and higher if the failure occures by pull out of reinforcing material. It cames from the law of similarity. However, the

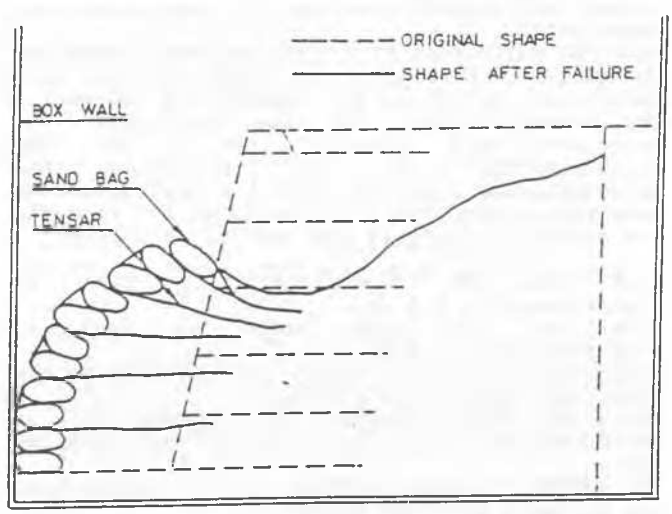

Fig. 6. The cross-section of the failed model in Case 2

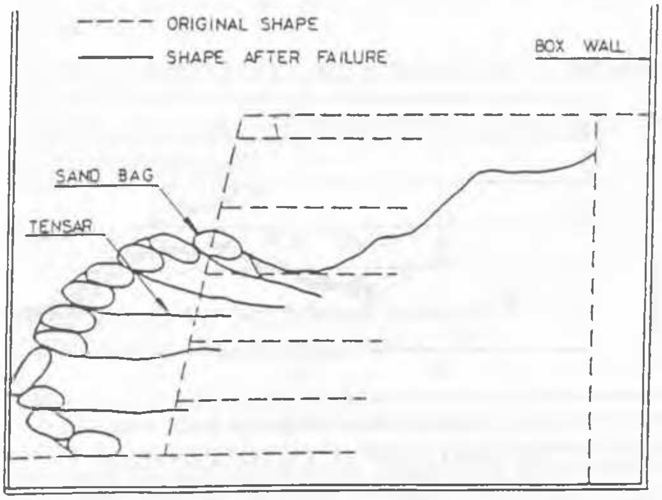

Fig. 7. The cross-section of the failed model in Case 3

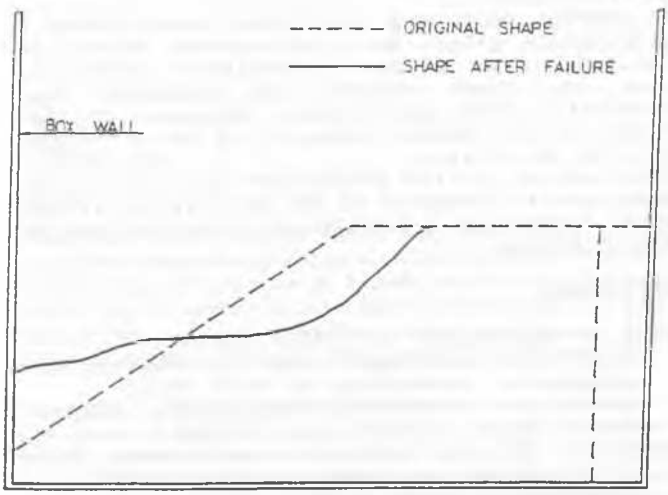

Fig. 8. The cross-section of the failed model in Case 5

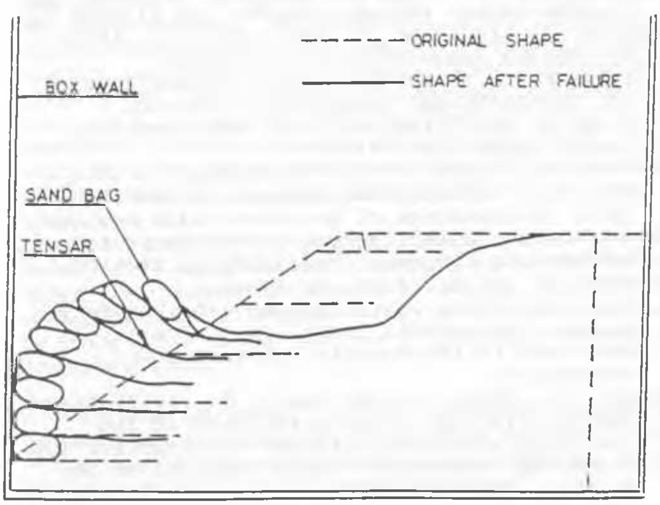

Fig. 9. The cross-section of the failed model in Case 6

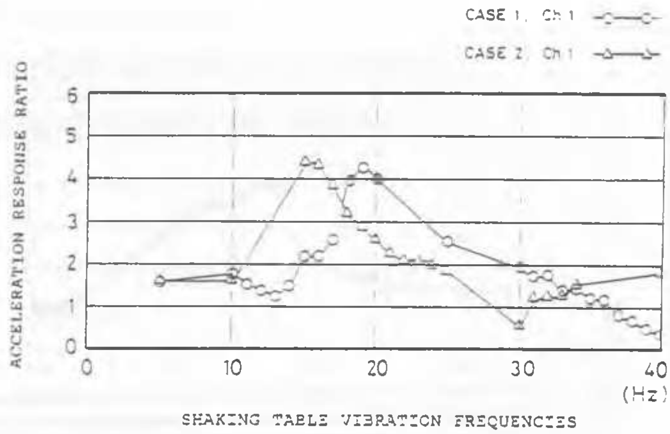

Fig. 10. The comparison of the acceleration response ratio of Case 1 and Case 2

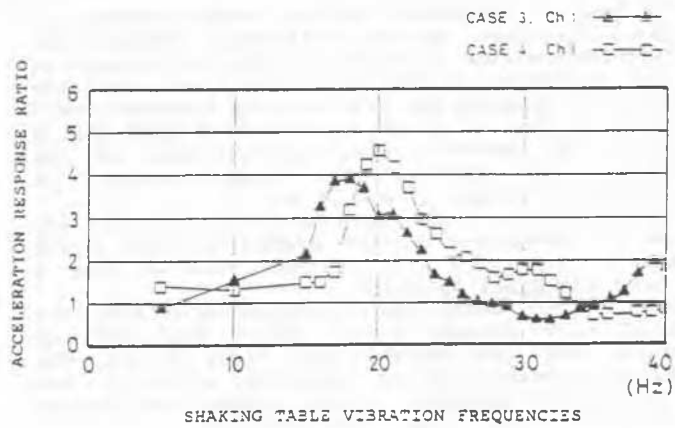

Fig. 11. The comparison of the acceleration response ratio of Case 3 and Case 4

different scale models have different eigenfrequencies. The differences are because of the scale of the models and fit well to the eigenfrequency of the prototype.
To analyze the failure characteristics of the different scale models the one sixth models were failed during the experiment in step 2, but the smaller scale one ninth models are not failed till 500 gal acceleration. This phenomenon is caused by the scale effect. Theoretically if the different scale models truly follow the law of similarity they have to fail about the same acceleration, because the scale ratio of acceleration in the law of similarity is $\lambda=1$.
The reason why only the one sixth models failed is that the effect of virtual cohesion is not the same in the different scale models as aboved mentioned.

The effect of the slope angle

The effect of the slope angle for the dynamic behaviour of the embankments can be analyzed from Case 4 and Case 6 where the model scale, the failure mode and the excitation wave were the same and only the slope angle was different.The comparison of the of the acceleration response ratios are shown in Fig. 12.
It is shown that the eigenfrequency of Case 4 is 20 Hz and the eigenfrequency of Case 6 is 24 Hz.

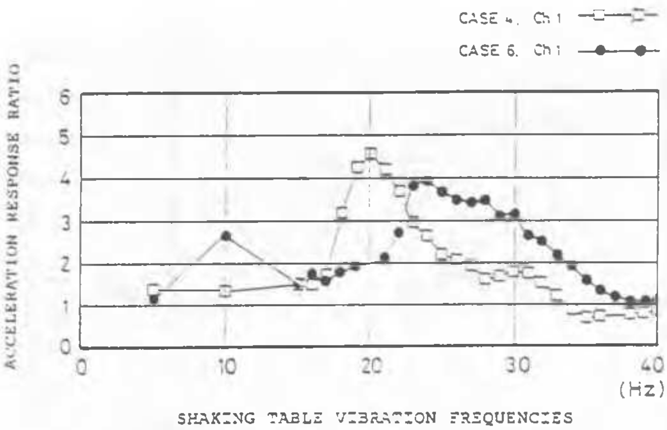

Fig. 12. Comparison of the acceleration response ratio of Case 4 and Case 6

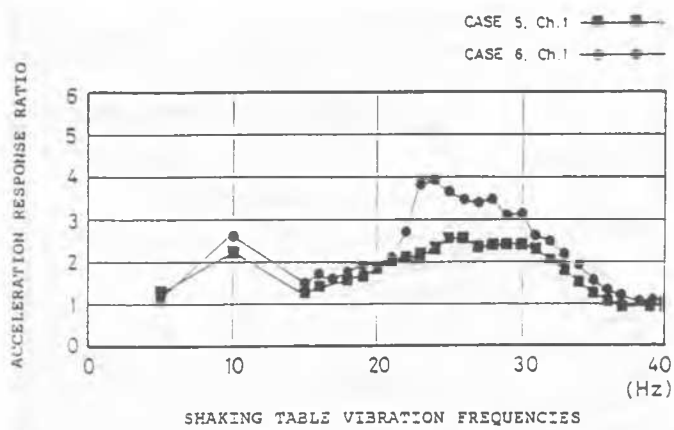

Fig 13. The comparison of the acceleration response ratio of Case 5 and Case 6

The mass of the models and the burden pressure is about the same, so the difference between the eigenfrequencies is come from the difference of the stiffness of the reinforced part and the shape. To analyze the acceleration response ratio curve of Case 6 it can be predicted that the 24 Hz is the second order eigenfrequency of the model. The first order eigenfrequency is somewhere between 10 and 20 Hz.

From step 2 of the experiments to analyze the failure behaviour of the models in Case 4 the model not failed till 500 gal, but in Case 6 there was model failure.

At first it seems as a contradiction that the model with steeper slope cannot fail and the other with less steep slope angle do so. The burden pressure has an important effect to the reinforcing material force. Higher the burden pressure in the surroundings of the reinforcement, higher reinforcing material force can act so, the reinforcing effect will be better. In the case of steep slope the initial vertical confined pressure can act in all the reinforced body, but in a not so steep slope there is an area where the initial vertical confined stress is ineffective. This is the explanation of the phenomenon, why only the model with a not so steep slope angle have been failed.

The effect of the reinforcement

The effect of reinforcement can be analyzed from Case 5 and Case 6. The models are the same except that in Case 5 the model has not been reinforced, but the model in Case 6 was reinforced.

The comparison of the acceleration response ratios of the models from step 1 of the experiment are shown in Fig. 13.

The comparison is made between the measured data of Channel one of the models. It is shown that the models have about the same eigenfrequencies, but the acceleration response ratio of the reinforced model much higher than the one of the unreinforced model. In Case 5 the maximum acceleration response ratio is 2.5 while the same value to Case 6 is 3.9. This difference shows that the reinforced model is much stronger than the unreinforced one. Both models are failed during step 2 of the experiments. The shaking table acceleration at failure of the models were:

Case 5: 189 gal
Case 6: 563 gal

So, if the reinforcement well designed and keep the law of similarity the effect of reinforcement is significant.

In general there are significant scale effect, slope angle effect and reinforcement effect of the models. So, if law of similarity cannot be kept and these effects are neglected the prediction from the dynamic behaviour of the models to the dynamic behaviour of the prototype will be not correct.

This mistake in the prediction will led to an uneconomical structure of the prototype or if the worst happens to a partial or total failure of the prototype.

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